Renewable and Sustainable Energy Reviews 20 (2013) 15–22

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

An overview of agricultural biomass for decentralized rural energy in Ghana

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ARTICLE INFO

Article history:
Received 5 April 2012
Received in revised form
17 November 2012
Accepted 19 November 2012
Available online 21 December 2012

Keywords:
Agricultural biomass
Decentralized energy
Rural Ghana

ABSTRACT

Efforts to improve the quality of life in rural areas rely upon the provision of electrical energy services. Globally, the focus is on identifying and maintaining sustainable and environmentally friendly energy resources, by means of the clean development mechanism (CDM). Supplying electricity by extending the grid to rural domains is, in most cases, economically unproductive, taking into account other related factors that pertain, especially in developing countries. Furthermore, an unfolding energy crisis in the sub-Saharan Africa (SSA) region intensifies the need for decentralized bioenergy applications using modern conversion techniques. Biomass energy produced in rural areas provides a sustainable alternative to grid electricity. This paper presents an overview of the potential of agricultural biomass-based resources for decentralized energy in rural areas of Ghana. It emphasizes the strategic importance of biomass energy, especially in areas where it is economically attractive because of the ready availability of resources. Assimilation of past and current research reported in the literature on biomass resources and bioenergy technologies in the country underpins this study. A more detailed evaluation of agricultural biomass-based potential was carried out and 2010 was chosen as the base period for the assessment. The result suggests that Ghana has a suitable potential of bioenergy resources and this holds considerable promise for future energy delivery in the country. The paper concludes with discussion of various promising decentralized bioenergy technologies for the exploitation of resources in Ghana.

Contents

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2012.11.047

1. Introduction

Biomass for decentralized power generation has been a rapidly growing concept in the power sector. In most developing countries, access to modern energy in rural and remote areas is critically difficult from the economic viewpoint. Direct connections of rural communities to a centralized power system impose serious burdens on developing countries, which are subject to integral constraints. Industrialized countries with mature economies and sophisticated power systems have already taken advantage of electrical power from both centralized and decentralized power supply systems. However, the traditional approach to electrical energy supply is to expand existing transmission and distribution networks so that unconnected communities can gain access [1].

In the light of the energy crisis in developing countries, the only realistic alternative for power production in rural and remote villages is, with few exceptions, a decentralized energy system structure. In off-grid rural and remote villages, decentralized power generation using distributed energy resources (DERs) is considered the most important strategic solution to energy problems. In most countries of sub-Saharan Africa (SSA), the capital cost of investment on large-scale power plant is unaffordable by both central and local government authorities. The global quest to sustain economic development and deliver a better standard of living cannot be disregarded, and energy supply has to be improved if socio-economic and technological transformation is to be secured. Since many developing countries are characterized by a series of rural settlements, biomass-based decentralized power generation is a workable option.

Hitherto, Ghana has had to import fuel for power generation, but financial and environmental concerns in rural communities now make renewable energy from biomass the best option. Decentralized generation promotes energy efficiency, lower transmission losses and use of renewable sources [2]. Today, biomass occupies fourth position in the global energy supply mix while accounting for 14% of the world's energy consumption [3]. The rapidly growing interest in biomass for energy is based on its availability in almost every part of the world. It is a major source of fuel for poor people in developing countries. The rate of consumption of biomass to supplement the energy needs of people in developing nations is very high compared to the developed world, as illustrated in Table 1, which shows the contribution of biomass to final energy consumption in different regions of the world.

Decentralized energy provision using biomass is a strategy for planning the demand side of the energy management system effectively. Separating out the demand side of the energy structure in different regions can aid understanding of income opportunities based on the availability of biomass resources [5]. Agricultural production in sub-Saharan Africa, especially in Ghana, is dominated by rural farmers with a low income. The widespread system of farming here is associated with manual and traditional techniques that are highly labor-intensive. Decentralized electrification operating on biomass can offer a better and more reliable supply of electricity and generate income derived from the use of farmers' local resources [6].

Table 1
The contribution of biomass in final energy consumption [4].

Region	Share of biomass in final energy consumption (%)
Africa	60.00
South Asia	56.30
East Asia	25.10
China	23.50
Latin America	18.20
Europe	3.50
North America	2.70
Middle East	0.30

At present, Ghana depends on oil imports to provide a large proportion of its domestic energy because of the low capacity of the country's refinery. The spatial distribution of rural settlements and sparse road network in poor condition make the transport of oils to rural areas difficult. As is well-known, deficiency in commercial energy supply such as electricity in a society can exacerbate social asymmetry in living conditions [7]. The application of biomass as a fuel for power, heat and automobile engines has the greatest mitigation potential of all the renewable sources in this respect [8–10]. In many developing countries, rural electrification generators operating on imported fuels have a cataloged history of failure. Therefore, the need to provide a biomass-based energy alternative is paramount.

This article reviews the literature concerning the potential of agricultural biomass in Ghana to provide a decentralized electricity supply and other forms of energy production. Although the article focuses primarily on agricultural biomass resources, other related biomass sources such as municipal solid waste (MSW) and liquid biofuels are also discussed, as they also have the potential to contribute to decentralized rural energy. Decentralized generation of electrical power and some promising biomass conversion technologies are also analyzed.

2. Methods and materials

2.1. The geography of Ghana and the energy access situation

Ghana is a West African country bordering Burkina Faso to the north, Côte d'Ivoire to the west, Togo to the east and the Atlantic Ocean to the south. The total land area of the country is 23,853 ha. The population is estimated to be 24,233,431, amounting to 0.35% of the world's population in September 2010 [11]. In 2007, Ghana recorded a gross domestic product (GDP) of US$7.2 billion [12]. The industrial sector in Ghana is one of the major drivers of the nation's economy and accounts for approximately 25% of total GDP [13]. The dynamic nature of the industrial sector compared to others within the same sub-region places more energy demands on the nation's power sector. Table 2 shows the general situation of energy access in Africa.

Most households in Ghana, especially in rural settlements, have hitherto relied heavily on the availability of traditional biomass from firewood and wood charcoal for their primary energy supply. It was reported in 2008 that 72% of total energy utilized in Ghana was obtained from firewood and wood charcoal. Crude oil for energy accounted for 22% and hydro occupied just 6%, as indicated in Fig. 1.

Excessive consumption of firewood and charcoal has been a general propensity in the entire region of SSA owing to low access to electricity. A critical look at electricity access in Africa, as presented in Table 2, reveals that about 20 countries in the SSA

Table 2
General situation of electricity access in Africa, 2005 [4,14].

Country	Electrification rate (%)	Population without electricity (million)	Population with electricity (million)
Angola	15	13.5	2.4
Benin	22	6.5	1.8
Botswana	38.5	1.1	0.7
Burkina Faso	7	12.4	0.9
Cameroon	47	8.7	7.7
Congo	19.5	3.2	0.8
Dem. Rep. Congo	5.8	53.8	3.3
Côte d'Ivoire	50	9.1	9.1
Eritrea	20.2	3.5	0.9
Ethiopia	15	60.8	10.7
Gabon	47.9	0.7	0.7
Ghana	**49.2**	**11.3**	**10.9**
Kenya	14	29.4	4.8
Lesotho	11	1.9	0.2
Madagascar	15	15.2	2.7
Malawi	7	11.8	0.9
Mauritius	93.6	0.1	1.2
Mozambique	6.3	18.6	1.3
Namibia	34	1.4	0.7
Nigeria	46	71.1	60.5
Senegal	33	7.8	3.8
South Africa	70	14	32.6
Sudan	30	25.4	10.9
Tanzania	11	34.2	4.2
Togo	17	5.1	1
Uganda	8.9	24.6	2.4
Zambia	19	9.5	2.2
Zimbabwe	34	8.7	4.5
Other countries	7.6	83.6	6.9
Sub-Saharan Africa	**25.9**	**546.9**	**190.7**
Algeria	98.1	0.6	32.3
Egypt	98	1.5	72.4
Libya	97	0.2	5.7
Morocco	85.1	4.5	25.8
Tunisia	98.9	0.1	10
North Africa	**95.5**	**6.9**	**146.1**
Africa	**37.8**	**553.7**	**336.8**

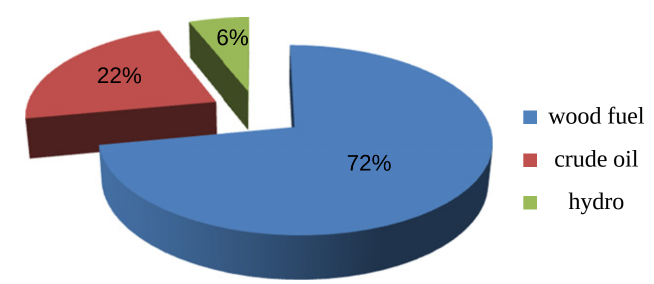

Fig. 1. Percentage contribution of primary energy supply in Ghana, 2008 [15,16].

region have less than 20% access. All five countries in the entire region of North Africa have more than 90% access, except Morocco, which has 85% access. In the sub-Saharan axis, Mauritius took the lead with 93.6%, followed by South Africa at 70% and Côte d'Ivoire at 50%. Ghana occupied fourth position, with 49.2% access. Rural areas are home to about 68% of the population [14] and they bear the brunt of Ghana's energy crisis.

2.2. *Biomass resources and production of their residues*

In developing countries, factors such as cultural preference, economic factors and resource availability compel many households to use more biomass than any other traditional energy resources [17]. Biomass is defined as biofuels derived from wood fuels, herbaceous energy crops, vegetable oils, animal and plant residues and other by-products with potential for energy application [18]. The various sources of biomass available in Ghana are presented in Fig. 2. Significant amounts of biomass resources are available in the country, providing a reasonable amount of energy potential. Data concerning production of agricultural biomass residues and other feedstocks selected for analysis in this paper are obtained from the Food and Agriculture Organization (FAO) of the United Nations database. The crops production data from FAO statistics are used for analysis, along with the corresponding quantities of residues, as well as energy potential, computed on the basis of conversion factors extracted from literature. This evaluation was accomplished based on nationwide data because county-by-county data on crop production are rarely available in Ghana owing to the widespread subsistence nature of agricultural production. Further, literature is thoroughly reviewed to support discussion on the subject of decentralized electricity generation using biomass conversion technologies.

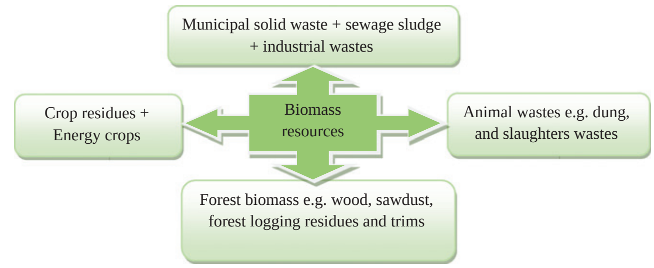

Fig. 2. Composition of biomass resources in Ghana.

3. Agricultural bioenergy resources in Ghana

Bioenergy resources are feedstock derived from biomass. Biomass from agricultural crop residues is mainly from cereal crop and animal residues. Major cereal crops grown in the country are sorghum, rice, millet and maize. Energy crop residues in the country are obtained from sugar cane, coconut, oil palm fruit, coffee, cocoa and jatropha. The residues of these energy crops are also useful biowaste for energy production and their potential for energy depends directly on their calorific values. Availability of bioenergy resources in Ghana depends on agricultural production input and the various agro-ecological farming zones, namely rainforest, deciduous forest, transitional, Guinea savannah, Sudan savannah and coastal savannah. Each of the zones is characterized by different mean annual rainfall and land area allocation.

3.1. *Biomass from agricultural crop residues*

Biomass from agricultural crop residues is divided into two major categories. The first category is obtained as a by-product of agricultural post-harvesting activities, usually from the processing of staple crops for domestic consumption. The other category is generated from industrial processing of agricultural crops. Cereal crop mills and food processing industries are directly involved in generation of biowaste agricultural residues. In some cases, these wastes may be part of municipal solid waste (MSW) in urban centers if they are not well disposed of.

Agricultural waste from fruit production is another biomass resource that could possibly be used as feedstock for anaerobic digestion. Fruit farming in Ghana ranges from small-scale practice to commercial plantations. Table 3 shows the main fruit species grown in the country, fruit yield, biomass residues and their

energy potential based on FAO statistics for 2010. Energy potential from biomass resources is divided into four types, representing a sequence of steps in the energy chain: theoretical energy, technical energy, economic energy and achievable energy potential [21]. The achievable potential in the actual sense is the usable energy potential that can be exploited from any biomass resource. Utilization of the potential of these resources depends on other energy inputs and logistical planning. In advanced countries, where there are sophisticated biomass utilization facilities, better achievable energy potential can usually be obtained. Table 4 presents the theoretical energy potential from various crop residues in Ghana. Energy potential of each crop residue is evaluated and the total potential is 86.60 TJ. The values chosen for the calculation of residue generated from maize, sorghum, sugar cane and groundnuts as the product-to-residue ratio (PRR) is obtained from Strehler and Stutzle [22]. According to Jingura and Matengaifa [23], these values are widely used for many crops in tropical Africa. Data for millet, oil palm fruit, rice paddy, cocoa beans and coffee PRR are taken from Duku, Ku and Hagan [13] and OECD/IEA [24]. The lower heating values of the crop residues were taken from Duku et al. [13] and NREL [25].

3.2. *Potential energy crops for liquid biofuel production*

Potential energy crops for liquid biofuel production in Ghana are jatropha, cassava, coconut, sugar cane, cocoa, coffee and oil palm fruit. Currently, Ghana has confirmed potential for biodiesel production from jatropha and oil palm fruit, both of which have received notable investment. Various private and government bodies are directly involved in funding oil palm fruit and jatropha production in Ghana. Jatropha plantation occupies over 1500 ha of land under the control of prominent institutions such as the UNDP, New Energy, Jatropha Africa Ltd., AngloGold Ashanti Ltd and Valley View University. This investment advantage places Ghana as the leading country for biodiesel production potential from jatropha in Africa [26], as shown in Table 5. According to DFID [27], the national government of Ghana has a vested interest in promoting the production and application of jatropha for biodiesel, thanks to the tendency of the crop to prosper in a wide range of environments and hence the possibility of creating job opportunities.

In the area of bio-ethanol production, the country is yet to embark on a comprehensive assessment of the potential of its naturally endowed resources, so information regarding

Table 3
Fruit species, yield, biomass residues generated and energy potential of the fruit (2010).

Fruit species	Yield (kt/year)[a]	Residue (kt)[b]	Energy potential (TJ)
Oranges	86	172	2.25
Bananas	88	176	2.31
Lemons and limes	68	136	1.78
Mangoes, mangosteens, guavas	100	200	2.62
Avocados	47	94	1.23
Plantains	108	216	2.83
Pineapples	60	120	1.57

[a] Fruit yield [19].
[b] Product to residue ratio (PRR)=1:2 and average energy content of 13.1 MJ kg^{-1} [20].

Table 5
Selected countries with major biofuel production potential in Africa [26].

Country	Raw material	Biodiesel ([a]ML)	Ethanol ([a]ML)
Benin	Cassava	–	20
Burkina Faso	Sugar cane	–	20
Côte d'Ivoire	Molasses	–	20
Ghana	**Jatropha**	**50**	–
Guinea Bissau	Cashew	–	10
Mali	Molasses	–	20
Malawi	Molasses	–	146
Kenya	Molasses	–	413
Ethiopia	Molasses	–	80
Niger	Jatropha	10	–
Nigeria	Sugar cane	–	70
Sudan	Molasses	–	408
Swaziland	Molasses	–	480
Senegal	Molasses	–	15
Tanzania	Molasses	–	254
Togo	Jatropha	10	–
Uganda	Molasses	–	119

[a] ML=megalitre.

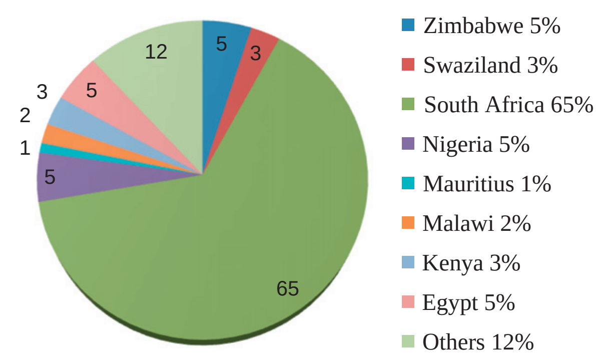

Fig. 3. Comparison of ethanol production in African countries [28].

Table 4
Agricultural crop residues and their energy potential.

Crop	Residue	Production quantity (10^3 t)[a]	Product to residue ratio (PRR)	Calculated residue generated	Lower heating value (MJ kg^{-1})	Energy potential (TJ)
Maize	Stalk	1872	1.4	2620.8	15.48	40.57
Sorghum	Stalk	324	1.4	453.60	17.00	7.71
Millet	Stalk	219	3.0	657.00	15.51	10.19
Oil palm fruit	EFB	2004	0.25	501.00	15.51	7.77
Rice, paddy	Straw	492	1.5	738.00	15.56	11.48
Sugar cane	Bagasse	145	2.1	304.50	13.38	4.07
Cocoa beans	Husk	632	1.0	632.00	15.48	9.78
Coffee green	Husk	1.2	2.1	2.52	12.56	0.03

EFB=Empty Fruit Bunch.
[a] Annual crop production in 2010 [19].

bio-ethanol production is scanty at present. In the entire Africa region, South Africa occupies a leading position in bio-ethanol production (see Fig. 3), thanks to a policy of focusing investment on biofuel from sugar cane.

The oil palm fruit business is also attracting attention for commercial production. Oil-bearing seed crops are a very promising raw material for biodiesel production in the country. Production of energy crops depends, however, on soil fertility, agricultural input and prevailing climatic conditions. Table 6 presents data on oil-bearing crops in Africa, clearly showing that Ghana has the potential to produce biodiesel from nearly all of the oil-bearing crops, with the exception of castor beans. Oil palm production in Ghana has been on the increase in the past ten years, making Ghana one of the leading countries in Africa with proven potential for biodiesel production from oil palm.

Table 6
Oil-bearing crops for biodiesel production in Africa [26].

Oil-bearing crop	Litre of oil/ hectare	Countries
Palm oil	5950	Angola, DRC, Nigeria, **Ghana** and Tanzania
Soya bean	446	DRC, Malawi, Republic of South Africa, Tanzania and **Ghana**
Coconut	2689	Nigeria, **Ghana**, Senegal, Mozambique and Tanzania
Jatropha	1892	All countries
Sunflower	952	Angola, Malawi, Nigeria, **Ghana**, Botswana, DRC, Mozambique, Republic of South Africa, Namibia, Zimbabwe, Zambia and Tanzania
Cotton seed	325	Angola, Malawi, Nigeria, **Ghana**, Tanzania, Mozambique, Republic of South Africa, Zimbabwe, Zambia and Tanzania
Avocado	2638	DRC, Republic of South Africa, Tanzania, Nigeria, **Ghana** and Senegal
Groundnuts	1059	Malawi, Angola, **Ghana**, DRC, Gambia, Senegal, Mozambique, Tanzania, Zimbabwe and Zambia
Cashew nuts	176	Angola, Mozambique, Tanzania, **Ghana**, Nigeria and Senegal
Castor beans	1413	Angola, DRC, Republic of South Africa and Mozambique

From Table 6, it can be clearly seen that Ghana has several varieties of oil-bearing energy crops that could be used for biodiesel production, although initiatives to use them for this purpose have not been effectively developed. Ghana is a developing country with a low pace of technological diffusion, especially in renewable energy.

Currently, research is ongoing into the production and application of ethanol for domestic energy in Ghana. The Center for Energy, Environment and Sustainable Development (CEESD) has initiated a study with Global Resolve, an NGO at Arizona State University, on the development of gel ethanol for cooking, the principal focus being to find an alternative cooking fuel to the commonly used firewood, in order to protect the environment. Gel ethanol is a mixture of ethanol and thickening substances capable of promoting the combustion efficiency of the fuel while minimizing indoor air pollution. To this effect, CEESD and Global Resolve have installed an ethanol distillation plant with 100 l capacity per day at Domeabra, a rural village in Ashanti Akim. Mount Olivet International School at Kwadaso-Kumasi and Domeabra Senior High School has been selected as sites where the fuel will be tested for cooking. The outcome of the experiment will determine the scale of production, investment issues and orientation for adoption. As part of its initiative for green energy development, the government of Ghana advocates effective partnership with private sectors, international bodies and non-governmental organizations, with the aim of accelerating the process of exploiting biomass exploitation for renewable energy before 2020.

3.3. *Agricultural bioenergy forest resources*

Forest biomass is mainly in the form of wood fuels. Biomass wood fuels mitigate carbon emissions in an efficient system in which they are used as feedstock to replace fossil fuels [18]. Various forest wood-based resources have been used as a major source of domestic bioenergy in Ghana. Wood fuel prepared in the form of firewood and charcoal has been used in Ghana to meet about 60% of final energy demand in the country [15,29]. Firewood from shrub lands, forest logging residues, wood charcoal and various forest residues have been used as core rural

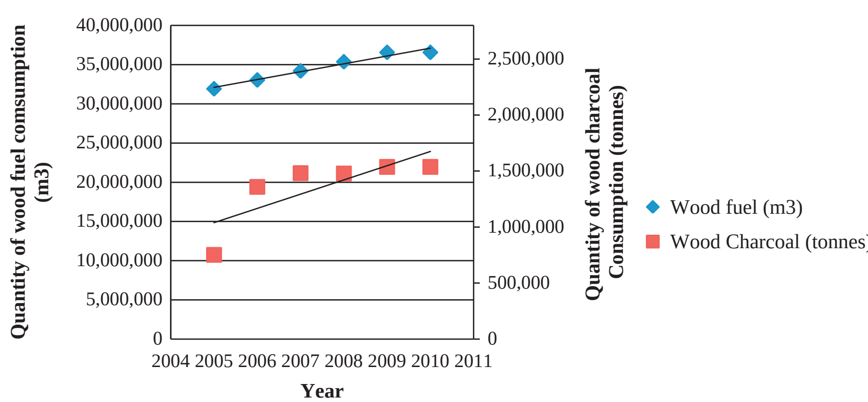

Fig. 4. A linear time-series graph for wood fuel and charcoal consumption in Ghana, 2005–2010 [31].

Table 7
Classification of fuel wood, description and examples [32].

Fuel wood	Description	Examples of the fuel wood
Indirect fuel woods	Mainly solid fuels produced from wood processing activities	Barks and sawdust from wood mills
Recovered fuel woods	Wood used directly or indirectly as fuel, derived from socio-economic activities outside the forest	Used wooden containers and pellets
Wood-derived biomass fuels	Liquid and gaseous fuels produced during forest activities by the wood processing industries	Black liquor from pulping of wood

energy sources. Ghana has several different kinds of forest tree species and is a member of the International Tropical Timber Organization (ITTO) in sub-Saharan Africa. In Africa, about 650 million hectares of land are forest cover, which is approximately 16.8% of the world's forest area [30]. The area covered by forest in Ghana was estimated in 2006 to be about 5.52 million ha, nearly 24.3% of the total territorial land [11]. Forest areas in Ghana are basically classified into two categories; open and closed forest. Based on the geographical distribution of the country, the open forest called savannah is found in the upper regions of the country while the closed type known as high forest is located in southern region. This accounts for the disparity in the potential of wood fuel for bioenergy decentralized generation between the two regions of the country. Besides domestic cooking and heating, the present situation regarding wood fuel consumption in some commercial applications like bread baking, cast iron handicraft and commercial food sellers also mainly use wood fuel as their source of energy.This has in no small measure contributed to a continuing decline in the reserves of the country's forest resources. Fig. 4 shows wood fuel and charcoal consumption in the period 2005–10.

In SSA countries, natural forest trees and woods are the core supporters of rural livelihoods and the rural economy. Utilization of biomass forest resources in Ghana is purely based on traditional methods. Forest ownership is a central issue in forest product utilization, and management and control of resources involve stakeholders such as central government, non-governmental organizations, stool land (communal land) owners and forest fringe communities. The Forestry Commission Authority of Ghana regulates the harvesting and disposing of forest resources in the form of annual allowable cut. However, poverty and the growth in population in the country have encouraged forest encroachment in the form of illegal logging and collection of wood fuel, bringing serious environmental and social challenges.

Forest biomass may be categorized into primary and secondary types. The primary type is the physical forest wood, which can be used directly for traditional or modern energy generation. The secondary type can be obtained by transformation of physical forest wood into by-products such as wood charcoal, sawdust and discarded logs. Another classification of wood fuel has three principal categories, namely indirect fuel wood, recovered fuel wood and wood-derived biomass fuels. Table 7 sets out the detailed classification of forest biomass resources.

Table 8
Livestock production quantity, total manure output and energy potential.

Livestock species	Production stocks[a] (1000 head)	Dry dung output ($Kg\ h^{-1}\ d^{-1}$)[b]	Total annual dung output (tonnes)	Energy value ($GJ\ t^{-1}$)[c]	Total energy potential (TJ)
Cattle	1454	1.80	955,278	18.5	17.67
Goats	4855	0.40	708,830	14.0	9.92
Pigs	536	0.80	156,512	11.0	1.72
Sheep	3759	0.40	548,814	14.0	7.68
Chickens	44,000	0.06	963,600	11.0	10.60

[a] Production stocks [36].
[b] Dry dung output [37].
[c] Energy value [37].

3.4. Agricultural biomass from animal manure

Animal manure can be a source of energy if well processed. In Ghana, livestock production generates a lot of biomass animal manure. Livestock farming consists of mixed farming and commercial livestock production. Mixed farming permits rural farmers and semi-urban households to breed a variety of livestock in small numbers. Commercial production involves the rearing of large numbers of a particular animal or closely related species of animals. Animals are moved from one place to another in a coordinated manner to access edible grasses. In some commercial operations, there may be an organized feeding system for the animals. Regardless of the production method, livestock farming yields a reasonable income and forms one of the backbones of the rural agricultural economy. Organic manure from animals is mostly treated by anaerobic digestion for energy production, a process that can benefit farmers for several reasons [33], and

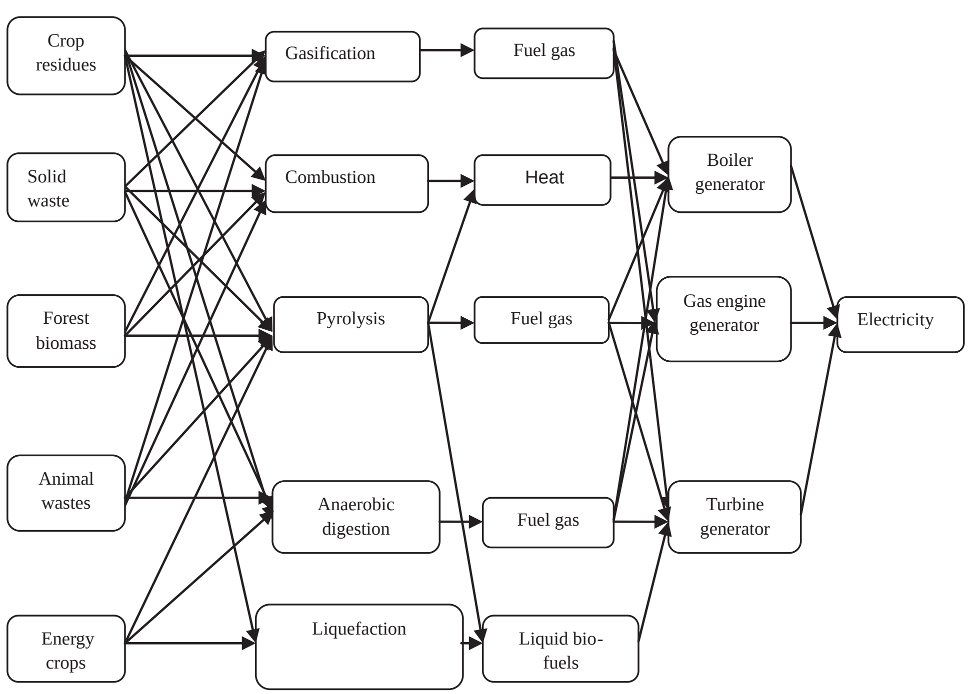

Fig. 5. Bioelectricity conversion pathways for decentralized energy generation [53].

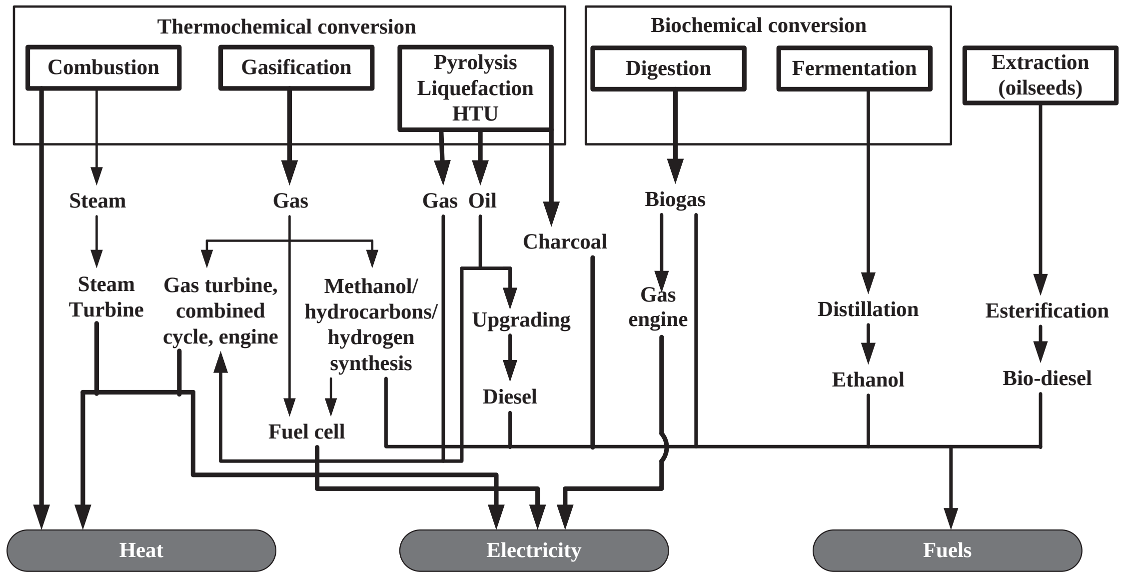

Fig. 6. Main biomass conversion pathway to energy and energy carrier [57–60].

additional income can be generated by the production and sale of biogas for cooking or electricity [34]. Table 8 presents information on livestock production and total manure generated. Animal waste manure production is determined by various factors including type of animal, physical body size, method of feeding, physiological state (lactating, growing, etc.) and level of nutrition [35].

As Table 8 shows, chickens are found in the highest numbers but produce the smallest quantity of waste per animal, although large quantities of manure can be expected when they are reared in large numbers. Cattle, being the largest animals, generate the highest total energy potential per tonne. For modern energy generation purposes, the manure is best utilized by first converting it to biogas through anaerobic digestion. Biogas is a methane-rich fuel produced from the anaerobic digestion of organic material, such as animal waste, dung and crop residues [38–40]. In the anaerobic digestion process, biogas is produced alongside anaerobically organic manure. The manure can be applied to an agricultural field after drying. The biogas can either be used for household cooking or to generate heat and electricity in a combined heat and power (CHP) plant, as widely used in European countries.

4. Decentralized generation of electricity using agricultural biomass

Sluggish progress towards widening access to electricity to rural areas in a large number of developing countries, through grid expansion, stand-alone and mini-grid, has left a significant proportion of the world's population without such access [41]. New approaches to planning for effective energy delivery systems are therefore called for, specifically integrated resource planning (IRP) of power supply and delivery systems characterized by elevated penetration of distributed energy resources (DERs) [42]. Rural energy development in Ghana and other SSA countries suffers from poor energy financing and incentive mechanisms, inadequate energy planning and the weakness of national energy policies. A simple solution is to base planning on local resources and allow community stakeholders to play active roles.

In order to provide electricity in rural communities in SSA, which has been slow, with the exception of South Africa [43], decentralized electricity generation has been considered as a mainstream alternative to the high cost of investment in grid electricity supply [44–47]. Scores of the world's most flourishing grid-extension programmes face high costs as they are being extended to more difficult-to-reach geographical terrain [48]. The inadequate progress towards providing satisfactory rural electricity has been attributed to a dedication to cost recovery, especially where projects are financed by private agents, and to a failure to raise the incomes of rural households and efficiently design tariffs and regulatory systems to make electricity more affordable [49]. Haanyika [50] states that the sparse distribution of rural settlements in the SSA region makes the costs of extending the electricity infrastructural network intrinsically high. Zvoleff et al. [51] conducted research into the influence of geography on the cost of rural energy infrastructure, finding that cost may be reduced, but not in all circumstances. Hence, decentralized generation provides a better alternative to grid extension in rural districts where distributed energy resources like biomass are available.

Rural electrification in developing countries needs to be sustained at the lowest cost. Therefore, decentralized distributed generation (DDG) consisting of small and geographically dispersed sources of electricity generation from renewable energy technologies (RETs) is a practicable alternative to grid-generated electricity [52]. Like wind, hydro and solar, agricultural biomass resources are DERs with a significant role to play in this respect. Biomass is the most viable choice in rural communities because it yields energy resources that can be used either alone or integrated, as shown in Fig. 5.

Off-grid energy delivery services may be more economically feasible than grid-connected systems [54], as shown by techno-economic analysis of rural electrification using stand-alone and grid-connected systems [55]. Biomass residues can be burnt directly to run a steam or sterling engine. Moreover, through the gasification process, they can be used to operate an internal combustion engine or a combined cycle power plant for electricity generation. Methane-rich biogas obtained from anaerobic digestion of biodegradable wastes from animal manure, human feces and municipal solid waste may be burnt in internal combustion engines for small-power production in rural communities. In some cases, biogas production can be enhanced by building a centralized anaerobic digestion system (CADS) using integrated organic feedstocks. Miscellaneous other biomass technologies such as pyrolysis, transesterification and liquefaction

(fermentation) can be used to produce bio-pyrolytic oil, biodiesel and alcohol, respectively, for operating internal combustion engines for electrical energy production.

5. Rural energy demands in Ghana and promising bioenergy technologies

The pattern of rural energy demand in Ghana is similar to that of other rural communities in the SSA region. Energy demand is basically for lighting, cooking and the powering of household appliances such as televisions, audio systems and electric motors for grinding food. However, most farming operations, especially irrigation and rural drinking water pumping machines, also need electricity for their operation. The water pumping load for irrigation is seasonal but drinking water is required continuously. Social and religious centers and schools also need electricity. The overall load connection of rural communities is quite low, as there is little or no commercial or industrial demand. Cooking activities dominate in the rural energy consumption profile [56]; they are mostly accomplished by high use of combustible biomass sources, but several studies have suggested biogas as a better substitute. Fig. 6 shows the main biomass-to-energy conversion pathways. As rural inhabitants generally live below the poverty line, unsubsidized energy running on imported fuel is beyond their reach. Thus, biomass energy resources would ensure a more cost-effective energy supply, promote efficiency of energy utilization, increase the economic potential of rural dwellers and enhance the possibility of diversifying renewable bioenergy resources for other purposes such as heat and biochemicals.

5.1. Promising bioenergy conversion technologies in Ghana

In general, the choice of biomass conversion technology depends on the type of biomass sources, resource accessibility and quantity of feedstock available. Solid biomass is typically handled by biomass thermo-chemical conversion processes, whereas wet biomass is preferably treated with biochemical processes. In the particular situation of Ghana, the five most promising biomass conversion technologies are fermentation, gasification, combustion, pelletization and anaerobic digestion.

5.1.1. Fermentation

This is basically a biochemical process for the production of ethanol from sugar and starchy crops. Sugar crops include sugar cane, sugar beet and sweet sorghum. Starch rich crops are maize, cassava, yam, potatoes and wheat. Production of bio-ethanol from these types of crops involves the action of enzymes and yeasts. To achieve good quality ethanol, purification of the raw ethanol produce is necessary. An additional advantage of fermentation is that the solid by-product obtained can be used for other purposes, such as bagasse from sugar cane as a fuel for electricity generation in a boiler or gasifier. In most cases, the ethanol-making power plants can utilize the residues for self-generation. Ethanol can be produced from a wide range of agro-based materials.

Ghana's potential for ethanol production is enormous. Bioethanol has a crucial role in greenhouse gas reduction if blended with petrol. Ethanol blended with petrol also tends to increase the oxygen content of the fuel, induce effective combustion of gasoline and reduce exhaust emissions of oxides of carbon and unburnt hydrocarbon, which are usually encountered with incomplete combustion in motor vehicles [61].

5.1.2. Gasification

Gasification is the application of heat in order to transform raw solid biomass feedstock into a mixture of gaseous products by chemical reactions at high temperature in an enclosed chamber called a reactor. The process of gasification involves four different stages: drying, pyrolysis, reduction and combustion. The collection of gases produced during gasification is called producer gas or syngas (carbon monoxide, carbon dioxide, hydrogen, methane and nitrogen). The syngas can be used in a highly efficient power generation system called combined cycle power plants, which combine steam and gas turbines [62]. Other products may be produced, depending on the chemical reactions induced.

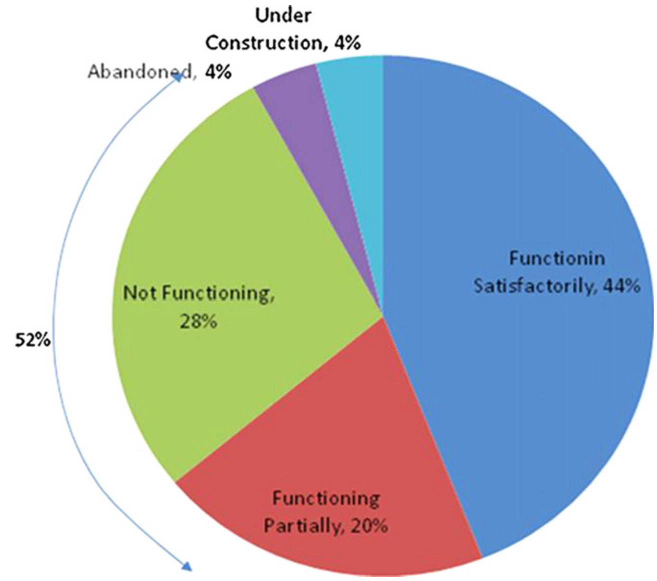

Fig. 7. Functional status of biogas plants in Ghana [75,76].

According to Ahiataku-Togobo and Ofosu-Ahenkorah [27], the biomass gasification process in Ghana is still at the stage of research and development and plant evaluation. Meanwhile, co-generation, also known as combined heat and power (CHP), is also operating experimentally in order to ascertain the feasibility of this method for using biomass resources from forest wood. A co-generation plant with a capacity of approximately 6 MW has been installed using sawmill residues and oil palm wastes as feedstock [13]. Gasification in the form of co-generation is rapidly gaining attention, as some small industries have begun to acknowledge the benefits of self-generation to deal with the power shortage in Ghana. This is one of the most promising bioenergy technologies for rural communities in Ghana, especially in the northern regions.

5.1.3. Combustion

The thermo-chemical conversion of biomass by combustion produces heat, which can then be converted into electricity. Combustion of biomass generates hot gases at high temperatures of 800–1000 °C [63] producing steam to run an internal combustion engine for electricity. At present, more than 90% of energy produced from biomass is generated using biomass furnaces [64,65]. Combustion is the most highly developed and market-proven biomass technology, whereas gasification is still in the development stage [66,67]. In addition, as much as 90% efficiency can be achieved by a modern biomass combustion plant and boiler, with minimal environmental effects [68]. Indeed, combustion of biomass, where it is available, has the potential to replace fossil energy [69]. No reports on biomass combustion in Ghana are yet available, but the availability of varieties of agricultural biomass residues from crop residues, forest residues and dry

Table 9
Profile of some selected biogas service providers [15,77].

Company	Date established	Workforce (full time)	Type of biodigester installed	Number of digesters installed
Biogas Engineering Ltd	2002	6	CAMARTEC fixed dome type, and effluent treatment plants	10
Biogas Technologies West Africa Limited (BTWAL)	1994	148	Fixed dome and effluent treatment plants	35
RESDEM	1996	N/A	Mostly bio-latrine digesters	25
UNIRECO	2001	5	Mostly bio-latrine digesters	N/A
Beta Construction Engineers Ltd	1975	25	Puxin biogas digesters	12

Table 10
Comparative analysis of energy obtained from direct burning of animal dung and biogas production [83].

Parameters	Direct burning	Biogas
Gross energy	10,460 kcal	4713 kcal
Device efficiency	10%	55%
Useful energy	1046 kcal	2592 kcal
Manure	None	10 kg of air dried

animal dung makes combustion a viable means of electricity generation.

5.1.4. Biomass pelletization

Biomass technologies for decentralized heat and electrical energy are still at premature stages of development, implementation and commercialization in Ghana. Biomass pelletization has no well-known history in biomass production and consumption in the country. Pellets are excellent and low-priced energy feedstocks to replace oil; they are renewable, almost unlimited in quantity and environmentally friendly [70]. Biomass pellets are solid fuels produced from residue feedstocks consisting of agricultural and forest biomass such as sawdust, straw and animal waste [71,72]. Biomass pellets are produced to increase the energy and mass density of residue feedstocks, which makes them easy to store and transport [73,74]. Biomass-based pellet feedstocks are used in many European countries in CHP facilities, notably in the Netherlands, Sweden, Greece, Germany and Denmark. The availability of agricultural biomass residues in Ghana provides an opportunity for biomass pellet production and consumption. Wood pellets produced from sawdust particles and chip residues from woods are a very clean source of energy. In the forest-rich south of the country, production of wood pellets may be possible even for commercial applications. This may also facilitate the establishment of systems of biomass pellet combustion and co-gasification for decentralized electricity.

5.1.5. Anaerobic digestion

Anaerobic digestion is one the fastest growing bioenergy technologies in Ghana. First-generation biogas facilities in Ghana had strong support from the government and originally focused on the provision of domestic cooking energy for rural and urban households [15], spreading later to various locations to satisfy other demands for electricity. Government agencies collaborated with some external developers and funding support organizations such as UNICEF, research institutes and non-governmental organizations. Compared to other counties in the SSA region, notably Nigeria, where there are only four small functional biogas plants, biogas application in Ghana has been successful, with hundreds of biogas digesters across the country. However, government funding of biogas development projects is currently reduced, as more attention is being given to grid extension for rural electrification, and as a result many biogas plants are either abandoned or not well-maintained, as shown in Fig. 7. In addition to lack of funding for maintenance, barriers to deployment and implementation of biogas technologies include shortage of raw feedstock and other economic challenges. Bensah [75] conducted a survey study of 50 biogas digester installations and users across Ghana, which found that 58% of installations are institutional, 28% are household units and the remaining 14% are community plants, underlining the need to encourage the deployment of more of the technology in rural communities. Biogas technology has obvious advantages for decentralized rural energy as it not only produces electricity but can also help improve environmental sanitation and the production of organic fertilizer for agricultural consumption. Anaerobic digestion has a long history in the country, as shown in Table 9.

The major commercial biogas providers in the country are companies owned by private individuals. These private companies and others in the biogas production sector are, with few exceptions, engaged in the provision of services for business purposes only. However, some biogas facilities with different capacities are installed in public places such as schools, prison yards and healthcare centers, under the supervision of the Institute of Industrial Research of the Council for Scientific and Industrial Research (CSIR-IIR), as part of the nation's bio-sanitation scheme. The facilities use more municipal solid waste (MSW) as biomass feedstock than animal manure. Animal manure is not widely used for biogas production because of its local application for energy by direct burning, although it has been the most common substrate for biogas production by anaerobic digestion [36] in many developed countries. Municipal solid waste with high fractions of biodegradables such as paper, cardboard and putrescibles is a potential feedstock for anaerobic digestion [78–82]. In the savannah region of the country, with its open forest, the burning of animal dung for domestic energy is common, owing to the perennial scarcity of firewood and wood charcoal. However, this method is associated with very low energy efficiency (see Table 10).

Biogas has been used in Ghana experimentally, under the Renewable Energy Program (REP) of the Ministry of Mines and Energy, to run an internal combustion engine for electricity generation in some rural communities, such as the Appolonia biogas power plant, where human excreta and cow dung are used as feedstock. The gas is fed to two 8 kW engines operating on dual-fuel mode connected to two generators with rated capacities of 5 kVA and 7.5 kVA. The total output of the generators is 12.5 kW electric power, which is supplied to the community via a local grid of 230 V electricity for 12 h per day [84].

5.1.6. Biodiesel production refineries

In the case of oil-bearing energy crops, oil has to be extracted first and then subjected to a biochemical reaction called transesterification in a chemical plant for biodiesel production. Biodiesel from vegetable crops has found important application in

automobile and diesel-based electric power engines. Commercial biodiesel refineries in Ghana include Anuanom Industrial Bio Product Ltd (AIBP), ScanFuel Company Limited and Biodiesel 1, Ghana Limited. According to Jumde et al. [26], the national biofuel policy prioritized biodiesel production, recommending the replacement of 5% of petroleum diesel with biodiesel by 2010, and 20% by 2015. In most rural communities, local methods are used to extract raw biodiesel oil from jatropha and, with time, development of small biodiesel production plants will occur, eventually leading to the emergence of small biodiesel-based electric power generators.

6. Concluding remarks

Increasing global concern to reduce environmental hazards, as maintained in the framework of the Kyoto Protocol, has widened interest in renewable energy development. In response to a continuing energy crisis, caused partly by inefficient use of energy resources, international communities and environmental activists have stepped up their campaigns to reduce consumption of fossil fuels and increase the use of renewable energy. Uncertainty regarding the prices of oil and gas is another major driver for bioenergy development. The main agricultural biomass residues (crop residues, fruit residues and animal manures) discussed in this study present a total energy potential of 148.78TJ. Biomass is the foremost renewable energy source in Ghana that can be relied upon to meet ever-increasing rural energy demand, thanks to its resource variety. It is obvious that demand for biomass puts great pressure on wood fuel from forests and that encouraging utilization of other types of biomass for electricity and heat supply would undoubtedly reduce that pressure, as well as enhancing the growth of natural forest and thereby increasing the potential of forest carbon stock to mitigate emissions.

Strenuous efforts are being devoted towards biofuel development in Ghana. Liquid biofuel resources are found in rural communities, where some of the residues generated during processing can be used for self-generated energy for raw material processing and electrification. Access to rural energy is widening, increasing the potential for profit and minimizing the cost of electricity to biofuel processing industries, which mostly depend on grid electricity and back-up diesel generators for energy.

Research on conversion technologies and policy issues in relation to the exploitation of agricultural biomass should be encouraged by the government and other energy stakeholders through adequate support programmes and provision of incentives, specifically to transfer the focus from forest resources to other bioenergy residues. Biomass has the highest socio-economic impact in rural communities of all sources of renewable energy. With improvement in biomass production and utilization and effective energy planning, household energy demand can be met in both rural and urban areas of the country, while also confronting energy-related environmental challenges such as global warming.

Acknowledgement

This work is put together based on the efforts for the sustainable energy development in sub-sahara Africa (SSA). The authors acknowledge Universiti Teknologi Malaysia and International Research and Development Institute (IRDI) Uyo, Nigeria for the provision of valuable materials in the make-up of this manuscript.

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